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Maslesa, Esmir; Nielsen, Susanne Balslev; Birkved, Morten; Hultén, Jannik

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Environmental indicators for non-residential buildings: When, what, and how to measure?

Esmir Maslesa
KMD, Technical University of Denmark DTU
xem@kmd.dk

Susanne Balslev Nielsen
Technical University of Denmark DTU, Oslo and Akershus College of Applied Science HiOA
susanne.nielsen@hioa.no

Morten Birkved
Technical University of Denmark DTU
birk@dtu.dk

Jannik Hultén
KMD
jik@kmd.dk

ABSTRACT

Purpose: The purpose of this research is to present state of the art within the scientific literature for assessing environmental building performance of non-residential buildings (NRB), and to guide facility managers' choice of environmental indicators to monitor the environmental performance of non-residential buildings like corporate buildings, public institutions etc.

Design/methodology/approach: 20 papers from a systematic literature review are analysed to determine main environmental building performance indicators/indicator sets as well as indicator management role and relevance in relation to the life cycles of NRB.

Findings: The reviewed literature states clearly that the use phase of NRB in general has the highest environmental impact in a building life cycle perspective. Furthermore, the literature reviewed identifies building environmental indicators in eight categories and determines two dominating assessment methods for compiling sets of indicators for assessing environmental building performance: The Life Cycle Assessment (LCA) method, and the criteria-based certification method with references to BREEAM, DGNB, LEED etc.

Practical implications: Decision makers such as building owners and facilities managers should focus on the building use phase in order to improve the environmental performance of NRB. Energy management is a topic of paramount importance, but not the only indicator category to be considered when addressing environmental building performance.

Based on our study, the paper recommends application of the LCA method for assessment of the building use phase and for improving the environmental performance of NRB. LCA can facilitate the determination of more environmentally friendly solutions based on lifetime calculations. Prior to LCA, Facilities Management (FM) data investigation should be conducted, in which the actual FM data regarding environmental performance should be evaluated.

Originality/value: This paper is a systematic literature review intended to provide the accumulated scientific knowledge on how to measure and manage environmental building performance. Such knowledge is relevant for facilities managers in the process of implementing an environmental strategy, but also for software developers who want to improve FM systems like e.g. Integrated Workplace Management Systems (IWMS).

Keywords: Facilities Management, Life Cycle Assessment, Building performance, Performance indicator, FM data.

1 INTRODUCTION

This paper provides an overview and conclusion about the most applied environmental building performance indicators. To limit the scope of the paper, the focus is narrowed down to non-residential buildings as a significant building type in most urban areas and due to their high energy and resource consumption (Abu Bakar et al. 2015; Balaban et al. 2015). Non-residential buildings (NRB) are in this paper defined as large corporate and public buildings with many users used for collective purposes.

The interest in environmental building performance assessment started to flourish already in the early 1960'ies with Silent Spring (Carson 1962). Since then, a significant amount of research has focused on the quantification of environmental impact of buildings, and appropriate environmental building performance indicators, but in various ways. Environmental impacts of buildings are typically summarized into two impact groups: embodied impacts (i.e., impacts embodied in the constructed building) and operational impacts (i.e., impacts occurring over the lifespan and hence use of the building) (Anderson et al. 2015; Soust-Verdaguer et al. 2016). Buildings as products are complex structures with a long service lifetime compared to most other products and they induce considerable environmental impacts throughout their life cycle (illustrated in Figure 1). The environmental performance of a building is dependent on many attributes: building design, selection of building materials, location, and use pattern which can be optimised through e.g. maintenance, renovations and changed use (Harris 1999; Pajchrowski et al. 2014).

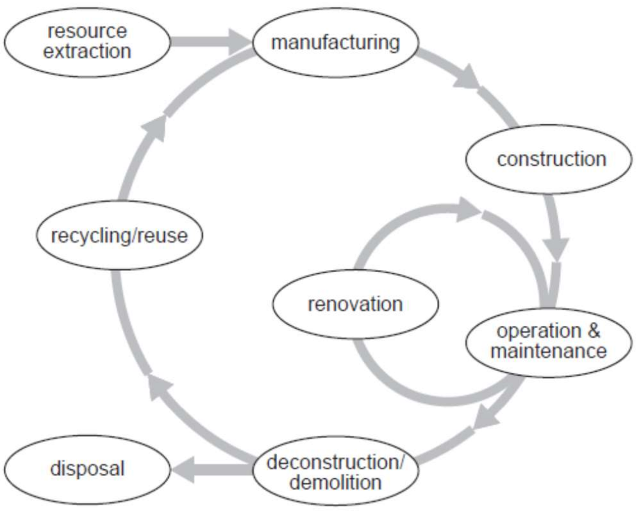

Figure 1 Schematic life cycle of a building (Melià et al. 2014).

Once designed and built, it is not easy to change environmentally impactful decisions made in relation to building design such as building orientation, window-to-wall ratio, and HVAC system (Russell-Smith et al. 2015). The processes used to operate and maintain buildings have an even larger cost and environmental impact than the design and construction process (Lewis et al. 2010). In fact, many of the environmental impacts of a building occur during its operational phase (Khasreen et al. 2009).

Relevant reviews of the FM literature have recently been conducted by Ebbesen (2015) and Nielsen et al. (2016). However, these reviews are lacking a comprehensive identification of studies specifically on environmental building performance indicators. To address this topic, our paper investigates the following research questions:

1. When in a building life cycle do non-residential buildings have the highest potential for improving environmental performance?
2. Which environmental indicators are most used for non-residential buildings?
3. How can environmental performance be quantified for non-residential buildings?

2 METHOD

A literature study is chosen as a research method for answering the research questions and to get an overview of recent research on environmental indicator categories for non-residential buildings. A systematic literature review was conducted according to Okoli & Schabram (2010) in the period March-September 2016. The literature was analysed to determine main environmental building indicator sets, their role and relevance in relation to non-residential building life cycle.

Journal selection and first screening round
The literature search was conducted using 5 research databases (DTU FindIt, Google Scholar, ScienceDirect, Scopus, Web of Science). Initial search on "building environmental indicator" in the selected databases returned 1,125 papers from 12 international journals. To limit the amount of results, the scope was further limited in terms of time and topic. The time limitation is set to include only journal papers published from 2010 to 2017. This limitation was introduced to include only more recent research. Furthermore, since the research focus is on the built environment, only papers addressing buildings are considered topic-relevant. Introduction of time limitation and topic-relevance criteria reduced the amount of papers to 107 and excluded 4 journals.

Second screening round
Each article title and abstract was studied in depth afterwards, returning in the end 68 papers from 8 journals on building environmental indicators. 20 of the 68 identified papers relate to non-residential buildings and they constitute the basis of this paper.

Data extraction and analysis
The method choice brings both benefits and limitations to the paper. The final choice of 20 peer-reviewed journal papers is a result of the systematic approach applied as well as broad and comprehensive literature study of internationally acknowledged research papers. On the other hand, relevant research conducted before 2010 is constrained by the time limitation. Since the paper is based on journal papers, it only considers academic literature in the review process, without taking practice into account.

The selected dataset is subsequently used to document and illustrate which building life cycle phases, environmental indicator sets and assessment methods are most often considered in research when addressing environmental performance of NRBs. The analysis is carried out through a quantitative approach in which the research literature has been used to quantify the amount of papers working with different building life cycle phases, environmental indicator categories and assessment methods. The analysis results are summarized in one table in section 3 Results showing which building life cycle phases, environmental indicator categories, and assessment methods are addressed in selected research papers. Based on findings from section 3, the conclusion is made in the end.

3 RESULTS

An overview of the overall results of our study is shown in Table 1. The table encompasses 4 column groups in which the first column lists all 20 research papers used in the study. Second column group is named Building life cycle phase and is divided in 4 building life cycle phases: Manufacturing, Construction, Operation & Maintenance (Use) and End-of-Lifetime phase. This column is used to determine which building life cycle phases are covered by the selected papers and relates to the first research question, when in a building life cycle do NRB have the highest potential for improving environmental performance. Third column group in Table 1 shows which environmental indicator categories are addressed in the selected literature, and is used for disclosing what environmental indicator categories are most frequently used for NRB. fourth column group presents assessment methods considered in research papers and is included for answering the last research question, how can environmental performance be measured in NRB. The assessment methods are distinguished in two main categories: Life Cycle Assessment (LCA) and Certification-based method.

Table 1 Results of a literature review of 20 research papers.

	Publication	**Building life cycle phase**				**Environmental indicator category**								**Assessment method**	
		Man	Con	O&M	EoL	Energy man.	GHG emissions	Land use	Water man.	Waste man.	IEQ	Building mat.	Reuse pot.	LCA	Certifi-cation tools
1	*Elle et al. 2010*														
2	*Lombera et al. 2010*		1	1	1	1		1	1	1		1	1		
3	*AlWaer et al. 2010*	1	1	1	1	1	1	1	1	1	1	1			
4	*Malmqvist et al. 2011*	1	1	1	1	1	1	1	1	1			1	1	
5	*Sharma et al. 2011*	1	1	1	1	1	1			1				1	
6	*Conte et al. 2012*	1		1		1		1	1	1	1				1
7	*Grant et al. 2012*			1			1					1		1	
8	*Kim et al. 2013*					1	1				1				
9	*Toller et al. 2013*					1	1			1				1	
10	*Asdrubali et al. 2013*		1	1	1	1	1	1						1	
11	*Cabeza et al. 2014*	1	1	1	1	1	1							1	
12	*Holopainen et al. 2014*			1							1				
13	*Seinre et al. 2014*			1		1		1	1		1	1			1
14	*Melía et al. 2014*	1				1	1	1						1	
15	*Napolano et al. 2014*	1	1	1	1		1					1		1	
16	*Russell-Smith et al. 2015*	1				1	1							1	
17	*Abu Bakar et al. 2015*	1	1	1	1	1									
18	*Balaban et al. 2016*			1		1	1		1		1				
19	*Munarim et al. 2016*	1	1	1	1	1	1	1	1				1	1	
20	*Kylili et al. 2016*					1	1	1	1	1	1		1		
	Totals:	10	9	14	9	16	14	9	8	7	7	5	4	10	2

Man: Manufacturing; Con: Construction; O&M: Operation & Maintenance; EoL: End of Lifetime

3.1 Building life cycle: When to improve environmental performance?

The results from Table 1 show that most papers (14/20) focus on Use (O&M) and Manufacturing (Man) phase (10/20) for non-residential buildings. The Construction phase (Con) and End-of-Lifetime (EoL) phase are considered in 9/20 papers. The results indicate that most research concentrates on the Manufacturing and Use phases, while there is less focus on environmental impacts during the Construction and EoL phases for NRB. The minor focus on Construction and EoL phase might be ascribed to the fact that the Construction phase is a goal-oriented process mainly focusing on a building assembly, while the EoL phase is often disregarded due to lack of data or is heavily simplified. On the other hand, most of the research is focusing on the Manufacturing and Use phases of NRB. The research on the Manufacturing phase concerns manufacturing of building materials and components as well as their characteristics in a relation to environmental building performance. The research on the Use phase usually studies different environmental building performance optimization possibilities like e.g. retrofitting projects.

Deeper analysis of the literature from Table 1 reveals that the operating energy for non-residential buildings usually accounts for 80-90% of the total impacts, while embodied energy accounts only for 10-20 % of the building total impacts. For example, Russell-Smith et al. (2015) refer to earlier research conducted by Junnila & Horvath (2003) and Junnila, S., Horvath, A., Guggemos (2006) who found that for commercial structures over 90% of life cycle energy consumption and 80% of carbon dioxide emissions stem from the use phase of the building. Russell-Smith et al. (2015) refer also to Scheuer et al. (2003) who found earlier that over 95% of the life cycle energy related impacts in a case study of a new university building are a result of use phase consumption. Asdrubali et al. (2013) note that up to 85% of the total impact of the office building stems from the operation phase, while the impact of the construction phase is between 14% (office building) to 21% (detached house). Another comparative study of 13 buildings (4 NRB) found that commercial buildings have more impact on the environment compared to the residential buildings (Sharma et al. 2011). Sharma et al. (2011) also conclude that 80–85% of the total energy use during the life cycle is used during the phase of occupancy/use. These data indicate that the maximum energy consumption occurs during the use phase, when a building is in use.

A comprehensive study of 73 cases from 13 countries conducted by Abu Bakar et al. (2015) found that the range of Energy Efficiency Index (EEI) among the case buildings was 150-400 kWh/m^2/year (primary) for residential buildings and 250-550 kWh/m2/year (primary) for office buildings, indicating that the EEI values of the office buildings are slightly higher than for the residential buildings covered by the case study. According to the researchers, this observation is caused by the different life cycle of office buildings and can be attributed to the fact that an office building generally requires more operating energy due to high occupant intensity, large electrical load usage and higher energy demand to maintain comfort conditions inside the building compared to the residential building.

Cabeza et al. (2014) present an example of an office building in Finland showing that the most of the impacts are associated with electricity use and building materials manufacturing. Particularly, electricity used in lighting, HVAC systems, heat conduction through the structures, manufacturing and maintenance of steel, concrete and paint, and office waste management were identified as the most impacting activities. In another example described by Cabeza et al. (2014), a 7.300 m^2 six-floor university building in Michigan, USA, was studied, showing that the use phase alone accounted for more than 83% of total environmental burdens.

Additionally, Cabeza et al. (2014) consider building life cycle prediction. The authors note that the building life cycle in previous research is ranging between 10 and 100- years, with 50% of the papers considering 50-year, 19% considering 40- year and 9% considering 80 or 100-year. These results are in accordance with our observations in which we also have noted different building life cycles (30-50-100 year), with a majority of research using 50-year period as a reference building life cycle.

Relating to building life cycle predictions, Grant & Ries (2012) argue that maintenance and service life prediction assumptions contribute significantly to environmental impacts, by as much as 4–25% depending on the impact category, which is also supported by the comparative study of office buildings in Europe and the United States, wherein maintenance impacts comprised 4–15% of the total impact (Junnila et al. 2006). Another comparative study of nine building envelope systems at Rinker Hall, university building in Florida, USA, concludes that maintenance impacts may range 2-55% of the total life cycle impact, depending on the assumed service life, the assumed maintenance regime, and the frequency and intensity of replacement (Grant & Ries 2012).

The results from this section highlight two important issues: First, the use phase of NRB accounts for majority of environmental impacts from a life cycle perspective; Second, the estimations on a building life cycle in the literature are diverse and range between 30 and 100 years, making the actual use phase period difficult to estimate.

3.2 Environmental indicator categories: What to measure?

Having determined that the use phase of non-residential buildings accounts for the majority of environmental impacts, the study moves forward to indicator categories mostly applied for assessing environmental performance of non-residential buildings.

The environmental indicators for NRB are in the literature usually grouped into several categories. For example, Kylili et al. (2016) distinguish the environmental KPI category into 12 sub-categories, while Toller et al. (2013) select six indicators for environmental monitoring of the Swedish building and real estate management sector. This paper presents eight main environmental indicator categories observed in the literature study (Building materials, Energy management, GHG Emissions, Indoor environmental quality, Land use, Reuse/recycling potential, Waste management and Water management) and shows which categories are most used in studies of environmental performance of NRB.

To gain a better overview, the results on Environmental indicator categories from Table 1 are converted into Figure 2. The figure shows that Energy management and GHG Emissions are the two most studied environmental indicator categories in the selected literature. Energy management is addressed in 16/20 papers, while 14/20 papers focus on GHG emissions. Energy management category relates to energy consumption, energy saving potentials, and energy supply (renewable, non-renewable energy) topics for NRB. GHG Emissions category addresses climate change impacts through the emissions of green-house-gases such as CO_2, NOx, SO_2 etc.

Land use and Water management are considered in 9/20 and 8/20 papers respectively. The land use category focuses on space management inside and around the NRB, and how efficiently building space is utilized etc. Water Management category includes water consumption, water saving potentials, water supply, water pollution etc.

The waste management category studied in 7/20 papers looks into how daily waste or building waste in NRB is produced, treated, disposed of etc. Indoor environmental quality (IEQ), addressed also in 7/20 papers, refers to indicators like thermal comfort, daylight, air quality etc. IEQ indicators are often described as social indicators, but since many IEQ indicators have an impact on environmental building performance, they are included as an environmental category in this paper.

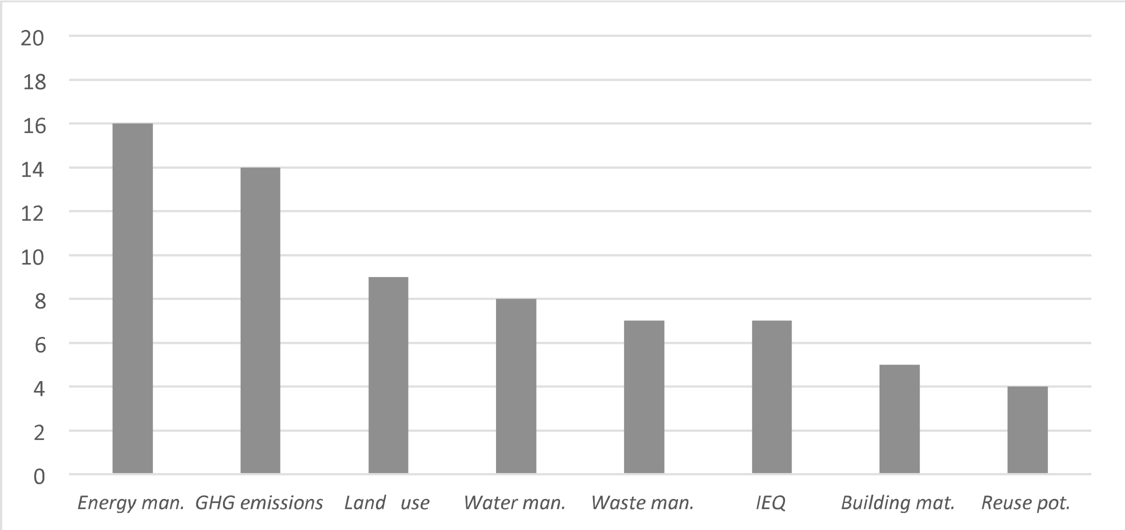

Figure 2 The amount of research papers addressing identified environmental indicator categories (n=20)

The least focus in the literature is on Building materials and Reuse potential: 5/20 papers consider building materials while only 4/20 papers focus on the reusing potential. The building materials category addresses building materials used for constructing the buildings. This category works with building material properties such as aesthetics, durability, thermal properties, maintenance properties etc. The reuse potential category looks into potentials for recycling and/or reusing existing building components and materials for other purposes after their ended lifetime.

Deeper analysis of the results from Figure 2 shows that most research conducted on environmental indicators for NRB is relating to energy management and GHG emissions. The literature study conducted by Abu Bakar et al. (2015) shows that the energy consumption in NRB is largely dominated by the Heating, Ventilation and Air-Conditioning systems (HVAC), and followed by lighting. A case study of six public buildings with retrofit actions points out that the most significant benefits related to energy savings and reduction of CO_2 emissions are mainly related to the improvement of the envelope thermal insulation (Cabeza et al. 2014). But the case study also concludes that substituting lighting and glazing components provide significant energy benefits. On the other hand, both solar and wind plants involve lower energy savings and higher payback indices than predicted. Furthermore, San-José Lombera & Aprea (2010) highlight that the sustainability of industrial buildings should not only be structured around energy consumption, but also include land, water, and material usage.

Research on IEQ points out that if higher comfort expectations in NRB are set as a target value, this could have a direct effect in building environmental performance, as a larger use of energy by the HVAC systems to maintain these comfort expectations is likely to be required (Holopainen et al. 2014; Seinre et al. 2014). IEQ indicators are also considered in Conte & Monno (2012) and Kim & Todorovic (2013).

Reuse potential of NRB is not covered substantially in the literature, but there is for example research showing that the recycling of building materials in masonry buildings generates environmental benefits due to avoided impact of virgin material production (Napolano et al. 2015). Related to reuse potential, Munarim & Ghisi (2016) look at building rehabilitations and present a case in which the construction of a new office building would take about 250 years to recover the investments in energy when compared with the adaptation for the same use of the old hotel Grand Central Arcade, Seattle. This is due to a very small difference in estimated operation energy consumption for the new and the rehabilitated building. The authors also argue that the lifespan of a building can be continuously extended by successive renovation, restoration or rehabilitation investments. In the end, Munarim & Ghisi (2016) conclude that the reuse of an existing building, through its rehabilitation, conserves natural resources and energy that would be used to build a new building.

The results from this section point out that most research relevant to our study focuses on energy management and GHG emissions. There is less focus on building materials and reusing potential, even though there might be hidden considerable potentials in these two categories for improving environmental performance of NRB.

3.3 Assessment methods: How to measure?

The results so far show that the research reviewed is mostly focusing on energy management and GHG emissions during the use phase of NRB, in which the highest environmental impacts from NRB also occur. But it is also relevant to know which assessment methods are applied when environmental performance of NRB is quantified.

There are two basic assessment approaches applied to obtain environmental indicator sets for buildings: the first one is based on LCA while the second one on the use of criteria-based certification tools (BREEAM, DGNB, LEED etc.). Certification tools are popular amongst practitioners, but can lead to erroneous conclusions, seen from a scientific point of view (Elle et al. 2010). When working with certification tools, it might be difficult to select relevant indicators from a broad range of data on the system under study, and since environmental quality does not refer to the objective characteristics of a building but is essentially a value-driven concept. Furthermore, criteria-based certification tools lack vital indicators that can be used to assess the sustainable performance of building envelope such as material efficiency, energy efficiency, economic efficiency and indicators with life time parameters such as life cycle cost, embodied energy etc. (Mwasha et al. 2011).

The results from Table 1 show that the LCA method is a dominating assessment method in research when it comes to assessing environmental building performance of non-residential buildings. Life-cycle assessment (LCA) has earlier proven (Lotteau et al. 2015; Anderson et al. 2015; Passer et al. 2016) to be an accepted scientific method for assessing environmental building performance, and its application is also evident in our literature study in which 10/20 papers apply LCA method for that purpose. On the other hand, only 2/20 papers consider certification tools for assessing environmental building performance of NRB.
LCA principles and the framework for life-cycle assessments are outlined by ISO 14040 and the requirements and guidelines are given in ISO 14044. In addition, the standard EN 15643 covers sustainability assessment of buildings (part 1-environmental, part 2-social, and part 3-economic). EN 15978 provides the calculations for the environmental assessment of buildings (Anderson et al. 2015).

There are two main approaches to data collection in LCA: process-based LCA and Input-Output LCA (IO-LCA). Process-based LCA is a bottom-up process analysis where the system is modelled by means of its specific information whereas IO-LCA uses economy or industry sector wide inventory data and break these down in a top-down process. A third approach, called hybrid-LCA consists in a combination of the two approaches (Lotteau et al. 2015).

4 DISCUSSION

The literature review has documented that the use phase of NRB is the most environmentally taxing life cycle phase. However, the literature itself is challenged when it comes to defining the lifetime of the building use phase. It is noted that the literature operates with different lifetimes for the use phase, and that these range between 30, 50 and up to 100 years (Cabeza et al. 2014). There is, of course, a relationship between material longevity, durability, and the natural differences between material assemblies and components (Grant & Ries 2012), but the use phase of NRB is also a variable highly depending on operation and maintenance (O&M) activities. A reliable building lifetime estimation is therefore an important prerequisite that needs to be considered when addressing environmental building performance of NRB.

Consequently, there is a need for a more dynamic LCA approach in practice that can illustrate the environmental impacts of different future scenarios and service lifetime of building materials and components, and not the conventional static LCA, as observed in most research published. However, the main barriers for applying dynamic LCA in practical building design include the perception that the LCA method is already highly data-demanding and work-intensive, and consequently costly. In addition, the use of LCA building tools is perceived to require a high degree of knowledge. Other barriers to the use of LCA in general include prejudices about the complexity, arbitrary results, accuracy and problems regarding the interpretation of results (Malmqvist et al. 2011). Furthermore, the application of the LCA method does not guarantee a reduction of emissions or energy consumption, but it allows highlighting the weak points of production process and identifying possible hotspots in the perspective of sustainable development (Proietti et al. 2013).

It is difficult to apply LCA to the construction industry because of difficulties in obtaining complete inventories for building components, tracking material flows and clearly defining system boundaries. Furthermore, Building Information Modelling (BIM) and FM software systems like Integrated Workplace Management Systems (IWMS) lack interoperability/interfacing with LCA and LCA software.

However, if the goal is to improve the environmental building performance of NRB, ALwaer & Clements-Croome (2010) argue that it is essential to design cohesive and coherent data management systems with a trusted format in order to ensure that the system performance is monitored properly, that reliable data is collected and that people are trained to analyse it for further use by decision makers, designers and facilities managers. It is advisable to think ahead so that data collected as part of a sustainability assessment can be reported as Key Performance Indicators (KPIs). The use of KPIs and benchmarking is fundamental to any improvement strategy and can be the right step in improving environmental performance of NRB. Combining actual FM data from FM systems like IWMS with LCA approach could provide improved system performance monitoring and deliver more realistic and reliable data on building performance, that later could be used for addressing and evaluating environmental building performance.

5 CONCLUSIONS

The literature reviewed states clearly that non-residential buildings have the highest environmental impact during their use phase. The operating energy accounts usually for 80-90%, while embodied energy requires 10-20% of the building total energy. Furthermore, the study notes that the use phase does not have a clear definition in the literature and that it ranges from 30 to 100 years, making the actual use phase period difficult to estimate.

Based on the results from our study, this paper suggests measuring following eight environmental indicator categories for non-residential buildings: Building materials, Energy management, GHG Emissions, Indoor environmental quality, Land use, Reuse/recycling potential, Waste management and Water management. The results also show that most research focuses on Energy management (16/20 papers) and GHG emissions (14/20 papers) categories, while there is less focus on Building materials (5/20 papers) and Reuse potential (4/20 papers).

Environmental performance for non-residential buildings can be quantified through two basic assessment methods: LCA models and criteria-based tools. Our study concludes that the LCA models are applied most (10/20 papers) to address environmental building performance of NRB. On the other hand, criteria-based tools are rarely considered in research (2/20 papers), while the research claims that they are popular in practice.

6 RECOMMANDATIONS FOR FURTHER RESEARCH AND PRACTICE

LCA and product system models can help facilities managers to choose more environmentally friendly solutions based on calculations taking the entire life time of buildings into account. However, further research is required to determine how LCA can be combined with FM in practice and to investigate which effects available FM data can have on optimization of environmental building performance. There is a need for mapping what kind of FM data is being used nowadays, its value and reliability, and how it can be collected, analysed and combined with LCA approach for optimizing environmental performance of non-residential buildings.

Based on the findings from this paper, we recommend the following for practice:

- Integrate environmental performance indicators with KPIs and FM systems for quantifying and managing building performance.
- Keep in mind that there are several environmental indicator categories to address.
- Consider how your FM data can be combined with the LCA approach to identify possible hotspots in facilities management for improving environmental building performance

REFERENCES

Abu Bakar, N.N., Hassan, M.Y., Abdullah, H., Rahman H.A., Abdullah M.P., Hussin F., Bandi, M. 2015. Energy efficiency index as an indicator for measuring building energy performance: A review. *Renewable and Sustainable Energy Reviews*, 44, pp.1–11.

ALwaer, H., Clements-Croome, D.J., 2010. Key performance indicators (KPIs) and priority setting in using the multi-attribute approach for assessing sustainable intelligent buildings. *Building and Environment*, 45(4), pp.799–807. Available at: http://dx.doi.org/10.1016/j.buildenv.2009.08.019.

Anderson, J.E., Wulfhorst, G. & Lang, W., 2015. Expanding the use of life-cycle assessment to capture induced impacts in the built environment. *Building and Environment*, 94, pp.403–

416. Available at: http://dx.doi.org/10.1016/j.buildenv.2015.08.008.
Asdrubali, F., Baldassarri, C. & Fthenakis, V., 2013. Life cycle analysis in the construction sector: Guiding the optimization of conventional Italian buildings. *Energy and Buildings*, 64, pp.73–89. Available at: http://dx.doi.org/10.1016/j.enbuild.2013.04.018.
Balaban, O. & Puppim de Oliveira, J.A., 2015. Sustainable buildings for healthier cities: Assessing the co-benefits of green buildings in Japan. *Journal of Cleaner Production*. Available at: http://dx.doi.org/10.1016/j.jclepro.2016.01.086.
Cabeza, L.F., Rincón, L., Vilariño, V., Pérez, G., Castell, A., 2014. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews*, 29, pp.394–416. Available at: http://dx.doi.org/10.1016/j.rser.2013.08.037.
Carson, R., 1962. *Silent Spring*, Available at: http://www.rachelcarson.org/SilentSpring.aspx.
Conte, E., Monno, V., 2012. Beyond the buildingcentric approach: A vision for an integrated evaluation of sustainable buildings. *Environmental Impact Assessment Review*, 34, pp.31–40. Available at: http://dx.doi.org/10.1016/j.eiar.2011.12.003.
Ebbesen, P., 2015. Information Technology in Facilities Management - A Literature Review., pp.1–14.
Elle, M., Dammann, S., Lentsch, J., Hansen, K., 2010. Learning from the social construction of environmental indicators: From the retrospective to the pro-active use of SCOT in technology development. *Building and Environment*, 45(1), pp.135–142. Available at: http://dx.doi.org/10.1016/j.buildenv.2009.05.011.
Grant, A., Ries, R., 2012. Impact of building service life models on life cycle assessment. *Building Research & Information*, 41(2), pp.1–19.
Harris, D.J., 1999. A quantitative approach to the assessment of the environmental impact of building materials. *Building and Environment*, 34(6), pp.751–758. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0360132398000584.
Holopainen, R., Tuomaala, P., Hernandez, P., Häkkinen, T., Piira, K., Jouko, P., 2014. Comfort assessment in the context of sustainable buildings: Comparison of simplified and detailed human thermal sensation methods. *Building and Environment*, 71, pp.60–70. Available at: http://dx.doi.org/10.1016/j.buildenv.2013.09.009.
Junnila, S., Horvath, A., Guggemos, A., 2006. Life cycle assessment of office building in Europe and the United States. *J. Infrastruct. Syst.*, (12), pp.10–17.
Junnila, S. & Horvath, A., 2003. Life-Cycle Environmental Effects of an Office Building. *J. Infrastruct. Syst.*, (9), pp.157–166.
Khasreen, M.M., Banfill, P.F.G. & Menzies, G.F., 2009. Life-cycle assessment and the environmental impact of buildings: A review. *Sustainability*, 1(3), pp.674–701.
Kim, J.T., Todorovic, M.S., 2013. Towards sustainability index for healthy buildings - Via intrinsic thermodynamics, green accounting and harmony. *Energy and Buildings*, 62, pp.627–637. Available at: http://dx.doi.org/10.1016/j.enbuild.2013.03.009.
Kylili, A., Fokaides, P.A. & Lopez Jimenez, P.A., 2016. Key Performance Indicators (KPIs) approach in buildings renovation for the sustainability of the built environment: A review. *Renewable and Sustainable Energy Reviews*, 56, pp.906–915. Available at: http://dx.doi.org/10.1016/j.rser.2015.11.096.
Lewis, A., Riley, D. & Elmualim, A., 2010. Defining High Performance Buildings for Operations and Maintenance. *International journal of Facility Management*, 1(2), p.16.
Lotteau, M., Loubet, P., Pousse, M., Dufrasnes E., Sonnemann, G., 2015. Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale. *Building and Environment*, 93, pp.165–178. Available at: http://www.sciencedirect.com/science/article/pii/S0360132315300445.
Malmqvist, T., Glaumann, M., Scarpellini, S., Zabalza, I., Aranda, A., Llera, E., Díaz, S., 2011.

Life cycle assessment in buildings: The ENSLIC simplified method and guidelines. *Energy*, 36(4), pp.1900–1907.
Melià, P. Ruggieri, G., Sabbadini, S., Dotelli, G., 2014. Environmental impacts of natural and conventional building materials: A case study on earth plasters. *Journal of Cleaner Production*, 80, pp.179–186.
Munarim, U., Ghisi, E., 2016. Environmental feasibility of heritage buildings rehabilitation. *Renewable and Sustainable Energy Reviews*, 58, pp.235–249.
Mwasha, A., Williams, R.G. & Iwaro, J., 2011. Modeling the performance of residential building envelope: The role of sustainable energy performance indicators. *Energy and Buildings*, 43(9), pp.2108–2117. Available at: http://dx.doi.org/10.1016/j.enbuild.2011.04.013.
Napolano, L., Menna, C., Asprone, D., Prota, A., Manfredi, G., 2015. LCA-based study on structural retrofit options for masonry buildings. *International Journal of Life Cycle Assessment*, 20(1), pp.23–35.
Nielsen, S.B., Sarasoja, A.-L. & Galamba, K.R., 2016. Sustainability in facilities management: an overview of current research. *Facilities*, 34(9/10).
Okoli, C., Schabram, K., 2010. A Guide to Conducting a Systematic Literature Review of Information Systems Research. *Working Papers on Information Systems*, 10(26), pp.1–51. Available at: http://sprouts.aisnet.org/10-26.
Pajchrowski, G., Noskowiak, A., Lewandowska, A., Strykowski, W., 2014. Materials composition or energy characteristic - What is more important in environmental life cycle of buildings? *Building and Environment*, 72, pp.15–27. Available at: http://dx.doi.org/10.1016/j.buildenv.2013.10.012.
Passer, A., Ouellet-Plamondon, C., Kenneally, P., John, V., Habert, G., 2016. The impact of future scenarios on building renovation strategies towards plus energy buildings. *SBE16 Zurich*, 124, p.2. Available at: http://dx.doi.org/10.1016/j.enbuild.2016.04.008.
Proietti, S., Sdringola, P., Desideri, U., Zepparelli, F., Masciarelli, F., Castellani, F., 2013. Life Cycle Assessment of a passive house in a seismic temperate zone. *Energy and Buildings*, 64, pp.463–472. Available at: http://dx.doi.org/10.1016/j.enbuild.2013.05.013.
Russell-Smith, S. V., Lepech, M.D., Fruchter, R., Meyer, Y.B., 2015. Sustainable target value design: Integrating life cycle assessment and target value design to improve building energy and environmental performance. *Journal of Cleaner Production*, 88, pp.43–51. Available at: http://dx.doi.org/10.1016/j.jclepro.2014.03.025.
San-José Lombera, J.T., Garrucho Aprea, I., 2010. A system approach to the environmental analysis of industrial buildings. *Building and Environment*, 45(3), pp.673–683. Available at: http://dx.doi.org/10.1016/j.buildenv.2009.08.012.
Seinre, E., Kurnitski, J., Voll, H., 2014. Quantification of environmental and economic impacts for main categories of building labeling schemes. *Energy and Buildings*, 70, pp.145–158. Available at: http://dx.doi.org/10.1016/j.enbuild.2013.11.048 [Accessed July 7, 2016].
Sharma, A., Saxena, A., Sethi, M., Shree, V., Varun, 2011. Life cycle assessment of buildings: A review. *Renewable and Sustainable Energy Reviews*, 15(1), pp.871–875.
Soust-Verdaguer, B., Llatas, C. & Garcia-Martinez, A., 2016. Simplification in life cycle assessment of single-family houses: A review of recent developments. *Building and Environment*, 103, pp.215–227. Available at: http://dx.doi.org/10.1016/j.buildenv.2016.04.014.
Toller, S., Carlsson, A., Wadeskog, A., Miliutenko, S., Finnveden, G., 2013. Indicators for environmental monitoring of the Swedish building and real estate management sector. *Building Research & Information*, 41(2), pp.146–155. Available at: http://www.tandfonline.com/doi/abs/10.1080/09613218.2012.749747.